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Extremely Long-Lived Charged Massive Particles as A Probe for Reheating of the Universe

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We discuss the impact of charged massive particle big bang nucleosynthesis(CBBN) to explore the nature of the reheating of the Universe in the case that a new extremely long-lived charged massive particle(CHAMP) exists. If the mass of the CHAMP is within collider reach and it's lifetime is longer than 10^4sec, the comparison between the CBBN prediction and observed ^{6}Li abundances may indicate nonstandard reheating in the early Universe without relying on details of the decay properties. Even if the CHAMP mass is outside the reach of colliders, the cosmological considerations may provide a nontrivial hint for the existence of such very heavy long-lived CHAMPs from the late Universe if the daughter particles are the dominant component of the present dark matter. We consider a low reheating temperature model as an example of the nonstandard reheating scenarios.

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INTRODUCTION

We are living in an interesting time for particle physics. The CERN Large Hadron Collider (LHC) experiment will start this year and may show exciting results soon. Also recent significant developments of cosmological and astrophysical observations have improved our knowledge of particle physics.

The fact that the large fraction of matter in the Universe is not accounted for by standard model particles motivates further considerations for the role of hypothetical particles in the early Universe and the connection to collider physics. Recent theoretical studies have shown the possibility of extremely long-lived charged massive particles(CHAMPs) [1, 2, 3, 4]. The search for CHAMPs and the determination of it's properties may be an exciting challenge for future collider experiments and cosmological observations.

Under continuous efforts in the past decade, the standard big bang nucleosynthesis(SBBN) theory has been well established to precisely predict the primordial light element abundances [5] and may be used as a probe to find or constrain new physics beyond the standard model in the late time Universe [6, 7, 8, 9, 10, 11, 12, 13, 15]. As recent papers have pointed out [7, 8, 9, 10, 11, 12, 13], if extremely long-lived CHAMPs existed in the early Universe, such a CHAMP might constitute a bound state with a light element after/during the BBN era and modify the SBBN prediction of light element abundances.[1] This might constrain the number density of long-lived CHAMPs depending on the lifetime.

The cosmological constraints on thermally frozen long-lived CHAMPs have been discussed [3, 4, 14]. In most of these papers, the standard radiation dominated Universe during the freeze-out of CHAMPs was assumed. In such a standard scenario, the relic density $\Omega_C \sim m_C^2$ and the number density $n_C \sim m_C$ where m_C is the mass of the CHAMP, which implies severe constraint for heavier mass. Recent analysis showed that the entire mass region may be disfavored by BBN if the lifetime is longer than 10^4sec [8, 13, 28]. [2]

On the other hand, above BBN constraints may not exclude the possibility of the discovery of CHAMPs with lifetime $> 10^4$sec. The violation of the above constraints does not necessarily mean contradictions but may indicate an evidence of additional new physics or lack of understanding of astrophysics. From this point of view, the importance of searching for extremely long-lived massive particles was also discussed in the context of the supersymmetric theory with a gravitino LSP [4].

In this paper, we discuss a possible impact of the discovery of extremely long-lived CHAMPs to explore the nature of the reheating of the Universe, where the standard scenario has assumed the radiation dominated Universe during and after the thermal freeze-out of the CHAMP relic density until the time when the present matter dominated the enegy of the Universe against the radiation. We focus on a low reheating temperature model as the possibility of the nonstandard Universe and extract constraints on the theoretical parameters. We calculate the relic density of CHAMPs frozen during/after reheating and estimate the CBBN prediction of primordial ^{6}Li abundance by using a recent estimation of the nuclear reaction rate [11] and without assuming the Saha equation for bound state formation of a CHAMP and a ^{4}He. We will find that the CBBN prediction of ^{6}Li is sensitive to the number density of CHAMPs and the lifetime around $10^3 - 10^4$sec. If the lifetime is longer

[1] The bound state formation and the fate of stable CHAMPs had been also discussed in earlier works [17].

[2] For the lifetime $> 7 \times 10^6$sec, this conclusion may be changed once CHAMPs are captured by protons [7]

than 10^4 sec, the comparison between observed ^{6}Li and the CBBN prediction can impose a relevant constraint on the reheating temperature, which may potentially become an interesting restriction on some class of models of reheating after inflation or models of late time entropy production [19, 20, 21]. [3]

LOW REHEATING TEMPERATURE AND THE RELIC ABUNDANCE OF CHAMPS

Here we consider the CHAMP production during/after reheating of the Universe. It is believed that the reheating of the Universe results from the thermalization of the decay products from the decay of coherent oscillations of a scalar field or the decay of some heavy massive particles such as moduli or gravitinos which do not thermalize with the thermal bath of SM particles after the energy dominated the Universe. Here we consider reheating due to the decay of a scalar field ϕ. For the case of a heavy massive particle such as moduli or gravitino, a similar discussion to this paper can be applied [23]. The reheating temperature is defined by

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_*(T_{\rm RH})}{45}}\frac{T_{\rm RH}^2}{M_{\rm pl}}, \tag{1}$$

where Γ_ϕ is the decay rate of the scalar field ϕ, $g_*(T)$ is the number of massless degree of freedom at temperature T and $M_{\rm pl} = 1.2 \times 10^{19}$GeV. In this paper, we call this a *low* reheating temperature scenario in which most of the decays of the scalar field ϕ occur after freeze-out of CHAMPs. The importance of particle productions during the reheating era and the difference from the standard radiation dominated Universe in thermally frozen nonrelativistic particles was discussed in [22, 23, 24].

We estimate the relic density of heavy charged species as a function of the mass and reheating temperature. [4] We consider a simple reheating model described by the following equations [22].

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi\rho_\phi$$
$$\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma_\phi\rho_\phi + <\sigma v> 2 <E_C> [n_C^2 - n_{\rm EQ}^2]$$
$$\frac{dn_C}{dt} + 3Hn_C = - <\sigma v> [n_C^2 - n_{\rm EQ}^2] \tag{2}$$

where $\rho_C = m_C n_C$, ρ_ϕ, ρ_R are energy densities of the ϕ field and radiation, H is the Hubble parameter, $H^2 = (8\pi/3M_{\rm pl}^2)(\rho_C + \rho_\phi + \rho_R)$ and $<E_C> = \sqrt{m_C^2 + (3T)^2}$. The kinetic equilibrium for CHAMPs and radiations is assumed. Also we assumed that CHAMPs annihilate into radiation or the particles in the final state rapidly convert into radiation. As the initial condition, we use $\rho_\phi = (3/8\pi)M_{\rm pl}^2 H_I^2$, $\rho_R = \rho_C = 0$. The initial Hubble parameter H_I is taken significantly early before the completion of reheating at Γ_ϕ^{-1} and the freeze-out of CHAMPs.

In this paper, we do not consider more complicated cases of reheating after inflation and assume that this is the last reheating of the Universe. But notice that $\rho_R = \rho_C = 0$ may not always be satisfied if this reheating occurs after the Universe went through radiation dominated once as a result of earlier reheating [28].

Here notice that we have assumed two things. First, we assumed that the branching ratio of the ϕ decay into CHAMPs and the secondary production of CHAMPs due to the ϕ decay products are negligible during reheating. If the branching ratio is not small enough, we have to take into account the additional nonthermal contribution to the CHAMP relic after CHAMPs freeze-out [23]. The simple solution would be $m_\phi < m_C$ and the other possibility was also discussed in [20]. Second, we do not consider the significant amount of decays of ϕ directly into hidden particles like gravitinos which has a very small coupling with standard model particles, that is, we assume that such a component of hidden particle does not exceed the relic density of present dark matter and does not overclose the Universe.

We are interested in the production of nonrelativistic particles during/after reheating. In this paper, we will use the analytical solution for thermally frozen CHAMP relic density of the above differential equations [22].

The particle freeze out during reheating may be classified into two cases, the case that chemical equilibrium is not established before freeze-out, and the case that chemical equilibrium is established. The annihilation cross section determines which of the two cases applies. Since we are interested in the production of CHAMPs, the minimal coupling would be the coupling with a photon. Assuming s-wave processes dominates, we have

$$< \sigma_{\rm ann} v > = \frac{4\pi\alpha^2}{m_X^2}\gamma \tag{3}$$

where we take $\gamma = 1$. Chemical equilibrium during reheating era is established before freeze-out if

$$\frac{T_{\rm RH}}{m_C} \; > \; 1 \times 10^{-6} \times \gamma^{-1/2}\sqrt{\frac{2}{g}[\frac{g_*(T_*)}{g_*(T_{\rm RH})^{1/2}}]}[\frac{m_C}{10^2{\rm GeV}}]^{1/2} \tag{4}$$

[3] Similar discussions to this paper may be interesting for colored or double charged particles [37].

[4] The constraint on stable CHAMPs from heavy isotope searches was discussed in a similar set up [25]. On the other hand, notice that strictly speaking, the constraint from heavy isotope searches is constraining only the primordial abundance of stable CHAMPs which in general depends on a cosmological model of the early Universe. A heavy isotope constraint on stable CHAMPs produced by cosmic rays does not depend on cosmological models, but it still has model dependencies on the cosmic ray production cross section of CHAMPs [26, 27].

This condition follows from $n_C^{\rm Max} > n_{\rm eq}(T_*)$ where $T_* = 4m_C/17$ for s-wave corresponds to the temperature at which most of the production takes place [22]. Notice that for the thermal freeze-out during reheating, the typical freeze-out temperature T_F may be $O(0.1) \times m_C$. If $T_F > T_{\rm RH}$ and the above condition is satisfied, the chemical equilibrium in CHAMPs will be established and the relic will freeze out during reheating, for example, for $T_{\rm RH}/m_C \sim O(10^{-3})$ and $m_C < 10^7$GeV.

For the nonchemical equilibrium production, the present time relic density of CHAMPs is

$$\Omega_C^{NT(Low)} h^2 = 0.13 \times (\frac{g}{2})^2 [\frac{g_*(T_{\rm RH})^{1/2}}{g_*(T_*)}]^3 [\frac{10^3 T_{\rm RH}}{m_C}]^7 \gamma \quad (5)$$

For the chemical equilibrium production, the final relic abundance is approximately given by $< \sigma_{\rm ann} v > n_C^{eq} = H(T_F)$ and by taking account of the dilution of the frozen relic until the reheating completes. The Hubble parameter during the reheating is $H = \sqrt{5\pi^3 g_*(T)^2/9 g_*(T_{\rm RH})} T^4/T_{\rm RH}^2 M_{\rm pl}$ [22]. Notice that $T \sim a^{-3/8}$ during reheating, so that $a(T_{\rm RH})^3/a(T_F)^3 = (T_F/T_{\rm RH})^8$ [22]. Then,

$$\Omega_C^{TH(Low)} h^2 = 3.3 \times 10^{-8} [\frac{g_*(T_{\rm RH})^{1/2}}{g_*(T_F)}] \frac{T_{\rm RH}^3 {\rm GeV}^{-2}}{\gamma m_C x_F^{-4}} \quad (6)$$

where $x_F = m_C/T_F$. The freeze-out temperature is fixed by the solution of $< \sigma_{\rm ann} v > n_C^{eq}(T_F) = H(T_F)$.

$$x_F = \ln[\frac{6\pi g}{\sqrt{10}\pi^2} \frac{g_*(T_{\rm RH})^{1/2}}{g_*(T_F)} \frac{M_{\rm pl} T_{\rm RH}^2}{m_C^3} \alpha^2 \gamma x_F^{5/2}] \quad (7)$$

Here we implicitly assume that the maximum temperature is higher than the freeze out temperature, which may constrain the initial energy density of the ϕ field. This case reduces to the known thermal freeze-out formula within a few 10 percent differences if we take the limit $T_{\rm RH} = T_F$. That is, in this limit, eliminating dilution,

$$\Omega_C^{TH} h^2 \simeq 4.2 \times 10^{-8} [\frac{1}{g_*(T_F)^{1/2}}] \frac{m_C^2 {\rm GeV}^{-2}}{\gamma x_F^{-1}} \quad (8)$$

$$x_F = \ln[\frac{3\sqrt{5} g}{\sqrt{2}\pi^2} \frac{1}{g_*(T_F)^{1/2}} \frac{M_{\rm pl}}{m_C} \alpha^2 \gamma x_F^{1/2}] \quad (9)$$

This gives roughly $n_C/n_H \sim 3 \times 10^{-4} (m_C/100{\rm GeV})/\gamma$.

CHAMP BIG BANG NUCLEOSYNTHESIS (CBBN)

Next we consider the impact of CBBN for the number density of CHAMPs. Recently it has been pointed out that the bound state formation of a CHAMP and a light element at lower temperature of the binding energy may change the nuclear reaction rates of BBN and eventually change the light elements abundance from SBBN [7, 8, 10, 12]. Especially Pospelov pointed out that because of the strong electro-magnetic field due to the bound CHAMP, CBBN may have significant changes in the nuclear reaction rates from SBBN's for radiative processes which are highly suppressed in SBBN [8]. The CBBN nuclear reaction rate for ^{6}Li production has recently been evaluated by the use of the state-of-the-art coupled channel method [11]. We use the reaction rate here. for $T < 100$keV,

$$< \sigma_{^6{\rm Li}}^{CBBN} v > = 3.4 \times 10 \times {\rm GeV}^{-2} \times (1 - 0.34(\frac{T}{10^9{\rm K}}))(\frac{T}{10^9{\rm K}})^{-2/3} e^{-5.33(\frac{T}{10^9{\rm K}})^{1/3}} \quad (10)$$

In this paper, we do not include decay effects and only consider effects of the CBBN on ^{6}Li. Actually in the case of sufficiently low abundances compared to the present dark matter relic density, the impact on ^{6}Li due to the decays will not be significant [6]. In this paper, we consider the case where the number density is smaller than ^{4}He but larger than other light elements. Then we can simplify the discussion of the capture of CHAMPs, that is, essentially the important part is only the capture by ^{4}He. Since elements heavier than ^{4}He are extremely rare, if the number density $n_C/n_p > 10^{-10}$, we can safely ignore the captures by elements other than ^{4}He to evaluate the number density of the bound state $(C, ^4{\rm He})$. [5]. After the capture by ^{4}He starts, the probability of CHAMP captures by elements lighter than ^{4}He is extremely small and can be safely ignored until the capture of protons starts at $T = 0.6$keV ($t = 7.2 \times 10^6$ sec). Once proton capture starts, the remaining free CHAMPs will be immediately captured by protons. In this paper, we do not consider the effect of the bound state with a proton which may have some impact on light element abundance including ^{6}Li. The approximation will be safe for the case of $\tau_C < 7 \times 10^6$sec. [6]

Assuming that the reheating temperature is high enough for thermal BBN to occur, we solve following

[5] The formation of the bound state with heavier elements than ^{4}He uses only a small fraction of CHAMP. But if the number density is not small relative to ^{4}He abundance, the bound state formation with heavier elements might have some impact on evaluating the primordial abundance of such heavier elements through CBBN processes, for example, in ^{7}Li, etc. [7, 12]

[6] However, the bound state formation with protons may decrease ^{6}Li through $^6{\rm Li}((C,p),\alpha)^3{\rm He}$ [7]. But the estimation assumed that the nuclear reaction does not have Coulomb suppression and the stability of the bound state during nuclear reaction, which may not be a good approximation for the case of proton captures because the Bohr radius of the bound state is large relative to typical nuclear size. For the other bound sate with D, T, etc. would only contribute the small production of ^{6}Li.

equations.

$$\frac{dn_{^4\mathrm{He}}}{dt}+3Hn_{^4\mathrm{He}}=$$
$$-<\sigma_{\mathrm{rec}}v>(n_Cn_{^4\mathrm{He}}-n_{(C,^4\mathrm{He})}\tilde{n}_\gamma)+\frac{1}{\tau_C}n_{(C,^4\mathrm{He})}$$
$$\frac{dn_C}{dt}+3Hn_C=$$
$$-<\sigma_{\mathrm{rec}}v>(n_Cn_{^4\mathrm{He}}-n_{(C,^4\mathrm{He})}\tilde{n}_\gamma)$$
$$+<\sigma^{CBBN}_{^6\mathrm{Li}}v>n_{(C,^4\mathrm{He})}n_D-\frac{1}{\tau_C}n_C$$
$$\frac{dn_{(C,^4\mathrm{He})}}{dt}+3Hn_{(C,^4\mathrm{He})}=$$
$$<\sigma_{\mathrm{rec}}v>(n_Cn_{^4\mathrm{He}}-n_{(C,^4\mathrm{He})}\tilde{n}_\gamma)$$
$$-<\sigma^{CBBN}_{^6\mathrm{Li}}v>n_{(C,^4\mathrm{He})}n_D-\frac{1}{\tau_C}n_{(C,^4\mathrm{He})}$$
$$\frac{dn_{^6\mathrm{Li}}}{dt}+3Hn_{^6\mathrm{Li}}=<\sigma^{CBBN}_{^6\mathrm{Li}}v>n_{(C,^4\mathrm{He})}n_{\mathrm{D}}$$
$$\frac{dn_{\mathrm{D}}}{dt}+3Hn_{\mathrm{D}}=-<\sigma^{CBBN}_{^6\mathrm{Li}}v>n_{(C,^4\mathrm{He})}n_{\mathrm{D}} \qquad (11)$$

where $n_\gamma=2\zeta(3)T^3/\pi^2$,

$$\tilde{n}_\gamma=n_\gamma\frac{\pi^2}{2\zeta(3)}\left(\frac{m_{^4\mathrm{He}}}{2\pi T}\right)^{3/2}e^{-E_{\mathrm{bin}}/T} \qquad (12)$$

where we take the binding energy of ^{4}He to a CHAMP E_{bin} =311keV [17]. We use the following recombination cross section:

$$<\sigma_{\mathrm{rec}}v>=\frac{2^9\pi\alpha Z^2_{^4\mathrm{He}}\sqrt{2\pi}}{2e^4}\frac{\tilde{E}_{\mathrm{bin}}}{m^2_{^4\mathrm{He}}\sqrt{m_{^4\mathrm{He}}T}} \qquad (13)$$

where $\tilde{E}_{\mathrm{bin}}=\alpha^2Z_C^2Z^2_{^4\mathrm{He}}m_{^4\mathrm{He}}/2$ [17]. [7] For a nonthermal photon emitted in the recombination process, we assume the rapid thermalization which would be valid in the deeply radiation dominated Universe, that is, we always assume thermal distribution for photon and also kinetic equilibrium for all light elements.

We evaluate ^{6}Li abundance by use of Eq.(11). We assume the Saha-type equation $n_{(C,\mathrm{He})}=n_Cn_{^4\mathrm{He}}/\tilde{n}_\gamma$ and $n_C=n_C^{in}e^{-(t/\tau_C)}$ for the number density of the bound state until $T=10$ keV, and connect to the set of differential equations of Eq.(11) for temperature below 10 keV and numerically solved them. At $T>$10 keV, since the photo-destruction rate $<\sigma_{\mathrm{rec}}v>\tilde{n}_\gamma/H>10^2$ and the bound state formation rate is also larger than the expansion rate of the Universe in the third equation of eq(11), the use of the Saha equation would be a good approximation. Failure of the Saha approximation may happen if $3H\sim<\sigma_{\mathrm{ann}}v>\tilde{n}_\gamma$, when the rate of bound state formation is faster than the expansion rate of the Universe. We also used a SBBN value for the light elements as the initial values.

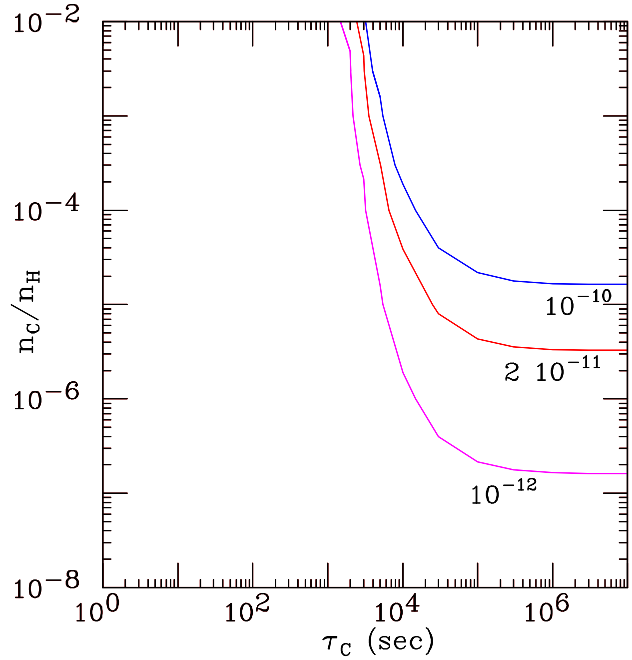

FIG. 1: Contour plot for ^{6}Li/H=10^{-10}, 2×10^{-11}, 10^{-12} as a function of the lifetime and relic number density of CHAMPs

In Fig.1, we show a contour plot of ^{6}Li abundance as a function of the lifetime and the number density of CHAMPs. Since the CBBN reaction rate D$((C,^4\mathrm{He}),C)^6$Li rapidly decreases due to the Coulomb suppression, most of ^{6}Li production occurs from $T=$ 10keV to a few keV. For a CHAMP lifetime $\tau_C>10^5$ sec, the ^{6}Li abundance is insensitive to τ_C. Also we found that the CBBN does not change D, ^{4}He abundances much through D$((C,^4\mathrm{He}),C)^6$Li.

In the last part of this section, we will make a few remarks. First, since CHAMPs would be metastable, high energy injections at late time due to the decays are expected and they could change the value of several light element abundances. But notice that the amount of the energy injection is in princeple independent from the number density which can be constrained by our discussion. Of course, in specific models, the effects may not be negligible. On the other hand, since the current good agreement with observations has disfavored large changes from SBBN predictions for D, ^{4}He, if we impose constraint on high energy injections from light elements other than ^{6}Li, our evaluation of CBBN production of ^{6}Li here still may provide the correct prediction. Of course, the late time energy injection itself also can change ^{6}Li

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[7] In this estimation of recombination cross section, a point particle for ^{4}He is assumed and only capture into the 1S state is considered. The estimation may have uncertainties from this assumption, the ignorance of the internal structure of nuclei and the contributions from captures into higher level, which directly reflct to the CBBN prediction.

without any big change of the other light elements if the energy release is large, which typically increases ^{6}Li.

The most stringent constraint on hadronic energy injections from several light elements is $\xi = Br_h\epsilon(n_C/n_\gamma) < 2\times10^{-13}$GeV at $t = 10^5$sec [6], where ϵ is the injected energy due to the decay and Br_h is the hadronic branching ratio of the decay. Roughly the above constraint implies that $n_C/n_H < 10^{-2}(100\text{GeV}/\epsilon)(Br_h/10^{-3})^{-1}$. Similarly, for $\tau_C > 10^7$sec, electromagnetic(EM) energy injections obtain $\xi = Br_{\text{EM}}\epsilon(n_C/n_\gamma) < 6\times10^{-13}$GeV from ^{6}Li/H [6], where Br_{EM} is the EM branching ratio of the decay, that is, $n_C/n_H < 3\times10^{-5}(100\text{GeV}/\epsilon)(Br_{\text{EM}}/1.0)^{-1}$. The EM constraints significantly weaken for $\tau_C < 10^7$sec. We do not expect a significant change for ^{6}Li abundance from our estimate in the region of Fig.1 if ϵ is not large. [8]

Next, if there is no significant charge asymmetry in the CHAMP sector, the positively charged and negatively charged CHAMPs can annihilate into two photons, W/Z or other SM particles. The energy release due to annihilation at $T\sim$10keV was estimated as follow [12, 15]:

$$\xi \sim 5\times10^{-13}\text{GeV}\left(\frac{100\text{GeV}}{m_C}\right)^{1/2}\left(\frac{\frac{n_C}{n_H}}{0.01}\right)^2 \tag{14}$$

Again comparing with $\xi < 2\times10^{-13}\text{GeV}(Br_h/1.0)^{-1}$, this effect would be irrelevant in most of the region of Fig.1.

CONNECTING ^{6}LI WITH THE REHEATING TEMPERATURE

In our scenario, the primordial ^{6}Li abundance depends sensitively on the reheating temperature. In Fig.2, assuming $\tau_C > 10^4$sec, we show the contour plot for $\Omega_C h^2 = 0.1$ which corresponds to the present dark matter relic density, and the contour plot for $n_C/n_H = 3\times10^{-6}$ where the number density of CHAMPs with $\tau_C > 10^6$sec may explain the observed ^{6}Li abundance $^6\text{Li/H} \simeq 2\times10^{-11}$. It is well-known that the SBBN prediction of primordial ^{6}Li abundance$\sim O(10^{-14})$ is much below the observed value. For long-lived CHAMP with $\tau_C > 10^6$sec, the ^{6}Li/H line may be a solution to explain the observed abundance of ^{6}Li by the primordial origin.

[8] The direct destruction of bound ^{4}He by CHAMP decays [9] may provide additonal contributions to ^{6}Li from $Q^2 < (1\text{GeV})^2$ in $\tau_C \sim 10^5$sec. But the discussion in $Q^2 < (1\text{GeV})^2$ is still uncertain. Also if the mass between CHAMPs and the decay product highly degenerate $\sim O(m_\pi)$ and the main decay mode happens through a coupling with a W-boson, new decay modes of bound states may have to be considered [16]. The destruction of ^{6}Li through this new decay mode can be important only if the capture of ^{6}Li process is efficient at $T < 10$ keV. In this paper, these contributions have not been included.

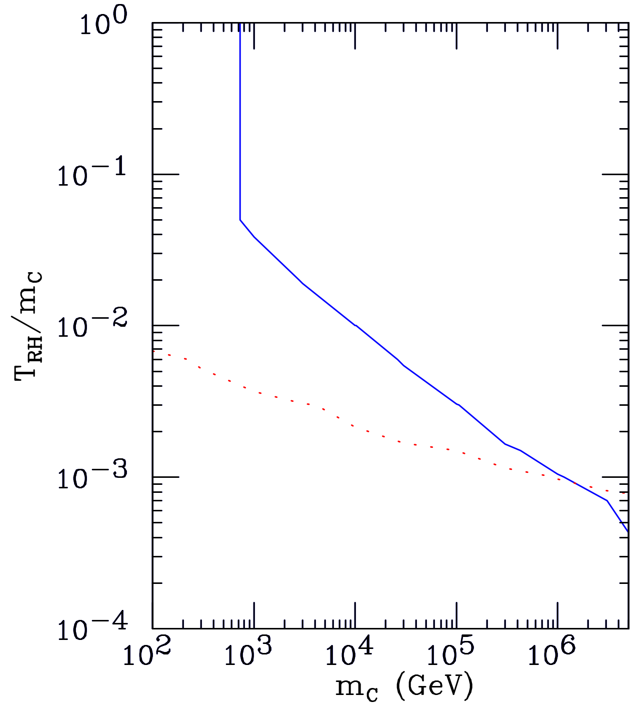

FIG. 2: Contour plot for the energy density $\Omega_C h^2 = 0.1$ (blue solid line) and the number density of CHAMPs $n_C/n_H = 3\times10^{-6}$ (red dotted line) as a function of mass of CHAMPs and reheating temperature assuming a specific reheating model of the Universe. $g_*(T_{\text{RH}})/g_*(T_F)^{1/2} = \sqrt{3.4}$ were assumed.

For the region above the line, ^{6}Li may be over-produced and potentially can constrain the reheating temperature for $\tau_C > 10^6$sec. On the other hand, it will require the knowledge of the late time evolution of ^{6}Li from the primordial era to the present time. As we can see in Fig.1, if the lifetime is shorter than 10^4sec, the constraint significantly weakens. A discovery of CHAMPs with lifetime longer than 10^4sec at a collider may indicate reheating beyond the standard scenario and put an upper bound of the reheating temperature for the models we are considering in this paper.

Several collider bounds on the mass of CHAMPs exist. On the other hand, the current most stringent constraint for CHAMP not decaying inside a detector is 98 GeV at 95% C.L. from CERN LEP at $\sqrt{s} = 209$GeV [29]. Currently there is no model-independent constraint through Drell-Yan processes at the Tevatron run-II. In the LHC, the bound may be extended up to 700GeV for 100fb^{-1} for an extremely long-lived charged slepton in the supersymmetric standard model [30]. For the mass regions within collider reach, the ^{6}Li line suggests lower reheating temperature $T_{\text{RH}}\sim$ a few GeV if $\tau_C > 10^4$ sec. The realization of such a low reheating temperature may be

a challenge for theoretical models after inflation. [9]

For the mass region above the collider reach, if such heavy CHAMP decays into a highly degenerate neutral particle, the relic density of present dark matter may link to the relic density of the CHAMPs like superWIMP dark matter scenario [32] and still their trace may appear in astrophysical observables. If heavy extremely long-lived CHAMP keeps the tight coupling with baryon-photon fluid until it decays, the small scale power of primordial fluctuation of CHAMPs would be erased within the scale of the sound horizon at the decay time, which has an impact on the small scale structure formation of the Universe [33]. To explain small scale problems like missing satellite problem, which may require damping of the power spectrum of dark matter at small scales, the lifetime $\sim 10^7$sec is preferred, where the CBBN ^{6}Li production may be expected. [10] To avoid large free streaming effects and additional cosmological constraints such as the cosmic microwave background black-body spectrum, tiny mass degeneracy may be favored, which means $\Omega_C h^2 \sim 0.1$ is the interesting region. We can find that such an interesting spot appears for $m_C \sim 10^6$GeV and $T_{\rm RH}/m_C \sim 10^{-3}$. The realization of the thermal leptogenesis scenario [35] may be possible if the maximum temperature is high enough to go through an electro-weak phase transition, which depends on initial energy density of the ϕ field.

CONCLUSION

We considered extremely long-lived CHAMPs as a probe of the early Universe. Such CHAMPs could leave their trace in astrophysical observables. The primordial ^{6}Li abundance in CBBN could be sensitive to the number density of extremely long-lived CHAMPs in the cosmic time $t \sim 10^{3-4}$ sec, and if the reheating temperature of the Universe is below the mass of the CHAMPs, in a model we considered in this paer, the relic abundance of the CHAMPs is also sensitive to the reheating temperature. That is, the observed ^{6}Li may indicate some information of the nature of reheating of the Universe. [11]

If the CHAMP mass is within the future collider reach, the measurement of the decay properties and the lifetime of CHAMPs are interesting challenges in future experiments [36]. Since the lifetime and several parameters associated with the relic abundance may be measured at collider experiments, by use of the inputs, we will be able to estimate the relic density of CHAMPs as a function of the reheating temperature and the effects on light element abundances. The further understanding of CBBN and late time evolution of ^{6}Li from the primordial era to the present time will help to understand the reheating nature of the Universe which may be a hidden part in the collider experiment itself.

Even if the mass range is outside of the collider reach, still the existence of CHAMPs may leave a trace on the power spectrum of the primordial fluctuation if the CHAMP was the parent particle of the present superWIMP dark matter [33].

As one of the attractive possibilities, the search for the superWIMP sector, e.g., in supersymmetric theory, is an interesting target in future collider experiments and cosmological observations.

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[9] The discussions on models that such low reheating is generic may be interesting [31].

[10] The rough estimation of the cut off scale is $\lambda \sim 0.265{\rm Mpc}\sqrt{\tau_C/{\rm year}}$.[34] Also the capture by ^{4}He will not disturb the discussion because the bound state would keep similar tight coupling with baryon-photon fluid to freely propagating case. Also since $n_C < n_{^4{\rm He}}$, the most of CHAMPs is captured by ^{4}He, so the conclusion may not be largely different from the case of no-capture.

[11] In the similar way, we also could consider the case of particle gravitational production due to expansion of the Universe during inflation [18].

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